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TITLE: REVERSE PRIMARY-SIDE FLOW IN STEAM GENERATORS
DURING NATURAL CIRCULATION COOLING

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REVERSE PRIMARY-SIDE FLOW IN STEAM GENERATORS
DURING NATURAL CIRCULATION COOLING*

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ABSTRACT

A TRAC model of the Large Scale Test Facility with a
3-tube steam-generator model was used to analyze natural-
circulation test ST-NC-02. For the steady state at 100% pri-
mary mass inventory, TRAC was in excellent agreement with
the natural-circulation flow rate, the temperature distribution
in the steam-generator tubes, and the temperature drop from
the hot leg to the steam-generator inlet plenum. TRAC also
predicted reverse flow in the long tubes.

At reduced primary mass inventories, TRAC pre-
dicted the three natural-circulation flow regimes: single phase,
two phase, and reflux condensation. TRAC did not predict
the cyclic fill-and-dump phenomenon seen briefly in the test.
TRAC overpredicted the two-phase natural-circulation flow
rate. Since the core is well cooled at this time, the result
is conservative. An important result of the analysis is that
TRAC was able to predict the core dryout and heatup at ap-
proximately the same primary mass inventory as in the test.

INTRODUCTION

The Japan Atomic Energy Research Institute (JAERI) ini-
tiated the Rig of Safety Assessment No. 4 (ROSA-IV) Pro-
gram in 1980 to obtain small-break loss-of-coolant accident
(SBLOCA) and operational transient data. The ROSA-IV Pro-
gram has three major objectives:

1. to conduct large-scale integral simulation tests of
   pressurized water reactor (PWR) SBLOCAs and op-
   erational transients using the Large Scale Test Facil-
   ity (LSTF),
2. to conduct separate-effects tests using the Two-
   Phase Flow Test Facility (TPTF), and
3. to develop and verify an advanced computer code.

The LSTF, shown schematically in Fig. 1, is a 1/48 volu-
metrically scaled, full-height model of a Westinghouse 4-loop
(3423 MW thermal power) PWR with an electrically heated
core (see Ref. 1). The facility has two equal-volume primary
loops, each one simulating the scaled volumes of two PWR
loops including a steam generator (SG). Each SG contains 141
full-size (19.6 mm ID) U-tubes having nine different heights.
Figure 2 is a schematic of the LSTF SG showing the dimen-
sions of the minimum- and maximum-length tubes and a table
giving the dimensions of all 9 tube types. The secondary vol-
ume and heat-transfer area in each SG are scaled at 1/24 of
those in the reference PWR. The hot legs are sized to con-
serve the ratio of the length to the square root of the pipe
diameter $(L/\sqrt{D})$ of the reference PWR for the simulation of
flow-regime transition in the primary loop.

In December 1985, two natural-circulation tests were con-
ducted at the ROSA-IV LSTF: ST-NC-01 at 5% of scaled
power and ST-NC-02 at 2% of scaled power. Reference 2 de-
scribes the results of test ST-NC-02. Natural circulation is
important in the cooldown of a PWR during certain classes
of accidents or transients involving an early trip of reactor-
coolant pumps. In these cases, decay heat from the core is
transported by natural circulation from the SGs, which act as
the major heat sinks. The natural-circulation flow rates are
quite small compared to the full-power flow rates. Single-
phase and two-phase circulation may occur as well as reflux
condensation.

Analyses of these natural-circulation tests with TRAC
were conducted at Los Alamos National Laboratory (LANL)
and at Idaho National Engineering Laboratory (INEL) as part
of the USNRC participation in the ROSA-IV program. Test
ST-NC-01 was analyzed at INEL (Ref. 3) and test ST-NC-02
was analyzed at LANL. This paper discusses the results of the
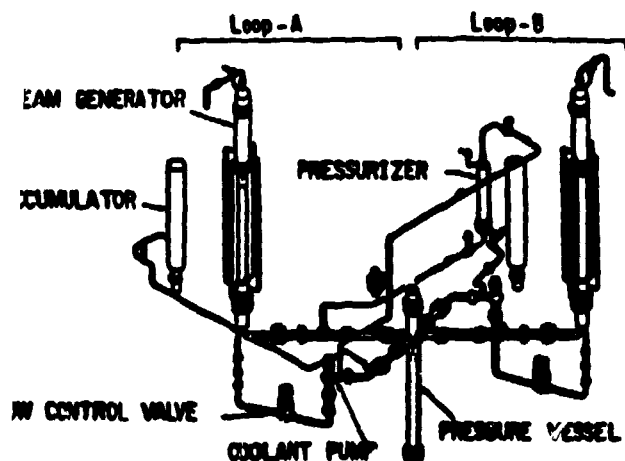analysis of test ST-NC-02.

MASTER

Fig. 1.
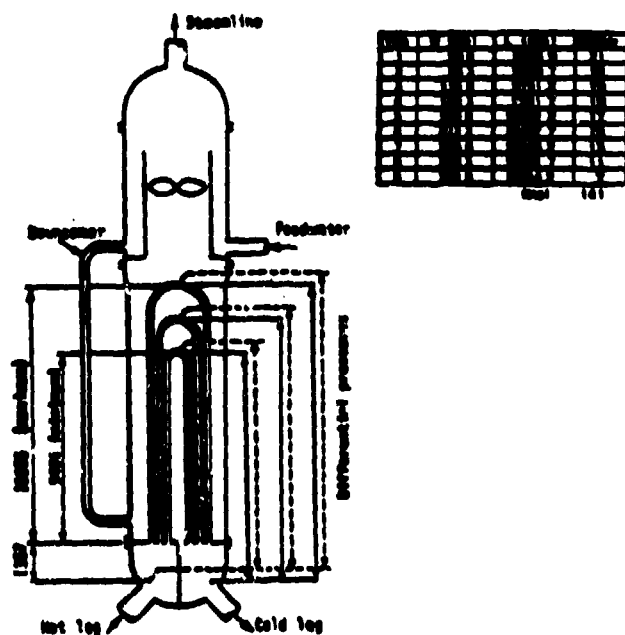Schematic view of the LSTF (Ref. 2).

Fig. 2.
Schematic view of LSTF SG (Ref. 2).

TRAC MODEL DESCRIPTION

The TRAC input model of the LSTF is quite detailed and simulates the primary system and the SG system up to the steam valves (see Fig. 3). The vessel consists of 15 axial levels, 2 radial sectors and 2 azimuthal sectors. Levels 3 to 9 and radial sector 1 represent the core. The SGs are modeled

with three primary tubes, which represent the short, medium, and long tubes (see Table I). The tubes are interconnected with PLENUM components. The grouping of the tubes is roughly equal, the medium-length group containing the greatest number of tubes. The first and last cells of each tube type represent half of the plena but include all of the heat-transfer surface area between the plena and the tube sheet. The secondary pressure is controlled by a constant-pressure BREAK component in the main steam line and the secondary-side water level is maintained by a FILL component and its associated controller.

The remainder of each loop is modeled with two TEE components to represent the hot leg and VALVE, PUMP, and TEE components to represent the cold legs. The pressurizer was not modeled explicitly but was represented by a FILL component to simulate primary-system inventory changes because of changes in the pressurizer level observed during the test. The pressurizer heaters were not used during the experiment. Although the valve in the pressurizer surge line was closed for most of the test (after the second drain), there was a gradual decrease in the pressurizer level during most of the transient. This indicates that there was steam flow in the spray line connecting the loop-A cold leg with the pressurizer. Because there was not enough geometric data available to model the spray line components accurately, a BREAK component was added to the cold-leg spray to simulate this flow. This permitted the primary-system pressure to be controlled to the primary-system pressure observed in the test.

TABLE I

COMPARISON OF THE LSTF SG WITH TRAC 3-TUBE SG MODEL

LSTF Steam Generator				TRAC Steam Generator Model			
Tube Type	R	L	N	Tube Type	R	L	N
1	90.5	9490.9	21	SHORT	65.2	9511.5	40
2	83.2	9580.7	10				
3	115.8	9741.3	10				
4	148.3	9901.7	16	MEDIUM	147.3	1998.2	85
5	180.0	10042.2	17				
6	213.3	10193.7	16				
7	245.0	10043.2	13				
8	270.2	10493.7	11	LONG	282.5	10873.9	40
9	300.0	10044.2	7				

R ≡ Radius of U-Bend (mm).

L ≡ Length: Top of tubesheet to start of U-Bend (mm).
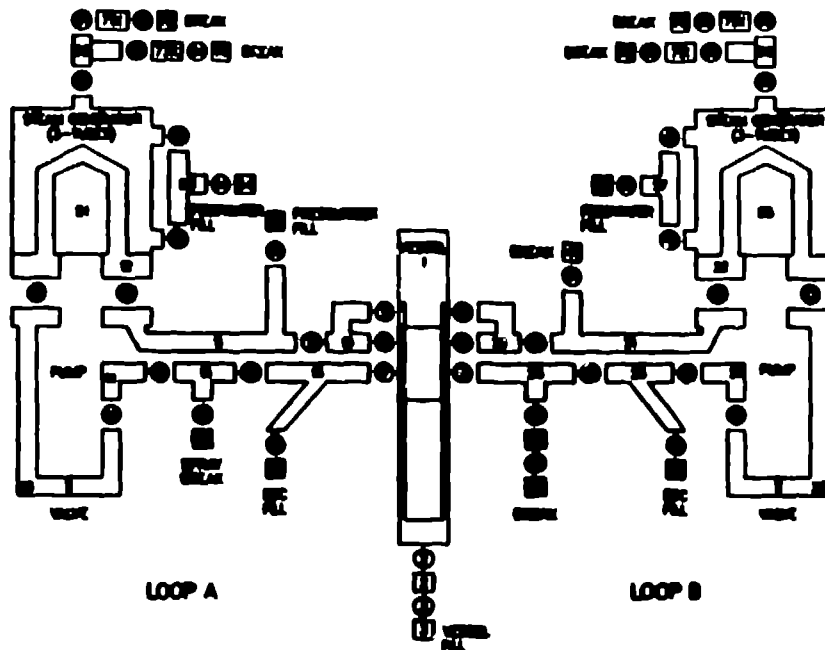
N ≡ Number of tubes.

Fig. 2.
Schematic view of LSTF SG (Ref. 2).

The ROSA-IV Test Facility SGs each have 141 U-tubes with 9 different lengths. The first TRAC model of the facility utilized a single-tube SG model (see Fig. 4). For loss-of-coolant accident (LOCA) tests, where the primary system voids rapidly, the detailed flow behavior in the SG tubes is not important to the short-term system behavior, and simulating the SG U-tubes by a single tube is adequate. For the natural circulation tests, however, the flow behavior in the SG tubes has a very important influence on system response. In addition, the flow pattern may be different in each tube.

In the experimental facility, six tubes in each SG were instrumented, representing the short, medium, and long tubes. In the test, the flow behaviors for the six tubes were quite different. In order to simulate this effect, a three-tube SG model was developed for the TRAC model of the ROSA-IV facility to replace the single-tube model (see Fig. 5). The criteria for dividing the 141 U-tubes of the ROSA-IV SGs into 3 groups were to have approximately the same number of tubes in each group and to place all tubes of a given length into one of the groups. This means that the flow pattern in each tube in the facility SGs is characterized by one of three behaviors, and this behavior is assumed to occur in all tubes of a given group (>40 tubes).

EXPERIMENTAL OBSERVATIONS

The tests were initiated from a steady-state, single-phase, forced-circulation mode at the nominal PWR operating pressure of 15.6 MPa. When the pumps were turned off and the loop flow rate decreased, natural circulation developed. Two interesting phenomena occurred in the SGs: the fluid temperature in the long tubes became uniform and in equilibrium with the secondary-side and the SG inlet plenum temperature was approximately 4 K below the hot-leg temperature in test IT-NC-02 (see Fig. 6).

The uniform temperature in the long tubes imply either stalled or reverse flow. Reverse flow would account partially for the temperature drop between the hot leg and the SG plenum. Under nominal operating conditions, there is less flow in the long tubes because of the longer flow path. Because of the lower flow rate, the fluid in the long tubes cools more rapidly than in the shorter tubes, and hot fluid penetrates only a short distance into the long tubes. When the pumps stop, the fluid in the long tubes rapidly cools to the secondary-side temperature. Reverse flow is possible because the outlet plenum pressure is slightly higher than in the inlet plenum. This pressure imbalance results because the cold fluid in the downflow leg of the SG tubes is heavier than the hot fluid in the upflow leg. Reverse flow in the long tubes would reduce this pressure difference.

Reverse flow may have occurred because of the reduced power level and slow pump speed prior to stopping the pumps. If the natural circulation conditions had been approached in a different manner, the results may have been different. The geometry of the hot-leg connection to the SG inlet plenum is such that in conditions of natural circulation the hot-leg fluid is directed toward the center of the plenum below the short- and medium-length tubes.

A simple mass and energy balance on the SG inlet plenum, neglecting wall heat transfer, indicates that a reverse flow of approximately 2.5 kg/s in the long tubes is necessary in order to account for the 4-K temperature drop from the hot leg to the SG plenum. Another possible reason that would account for part of this temperature drop is heat transfer in the SG plenum across the plenum divider plate and across the tubesheet into the secondary fluid.
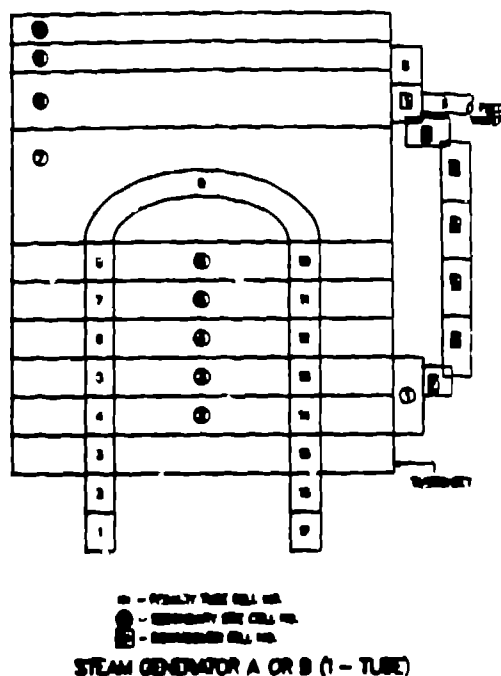
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STEAM GENERATOR A OR B (1 - TUBE)

Fig. 4.
Single-tube SG TRAC model.

STEAM GENERATOR A OR B (3 - TUBES)

Fig. 5.
Three-tube SG TRAC model.
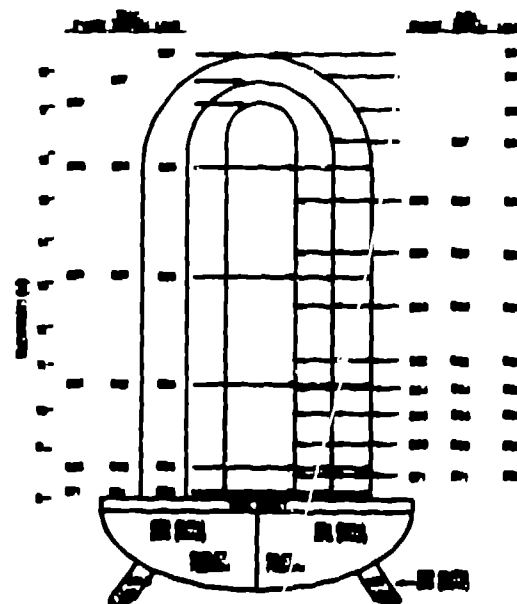
Fig. 6.
TRAC/data comparison of primary-side temperature distribution in SG A: 100% primary mass inventory.

modes, significant nonuniform flow distributions were observed in the SG tubes.

When the primary-side mass inventory was initially decreased, the loop flow rate increased because of voiding, which increased the static head between the upflow and downflow sides of the SG U-tubes and between the downcomer and riser in the vessel. A further decrease in the primary-side inventory decreased the loop flow rate because of the voiding at the top and downflow sides of some of the SG tubes. As the primary mass inventory was decreased, further natural circulation was interrupted as the top of all the SG U-tubes voided and the flow regime shifted to the reflux condensation mode. Eventually further decreases in the primary-side mass inventory results in core dryout. At a mass inventory of less than 30%, the tops of the highest-power rods began to heat up (Ref. 4) and the natural-circulation test was terminated at this time.

TRAC-DATA COMPARISONS

A. Steady State

To determine whether TRAC could simulate the natural-circulation flow patterns seen in the ROSA-IV facility SGs, the one-dimensional, single-tube primary-side SG model shown in Fig. 4 was replaced with a model that has three primary tubes to model the short, intermediate, and long tubes (see Fig. 5). The TRAC calculation was initiated with loop flows set to zero and uniform temperature distributions for the primary fluid in the SG tubes, the long-tube temperature being set to the temperature of the SG secondary side. Natural-circulation flow started immediately with forward flow in the short and medium-length tubes and reverse flow of approximately 1.75 kg/s in the long tube.
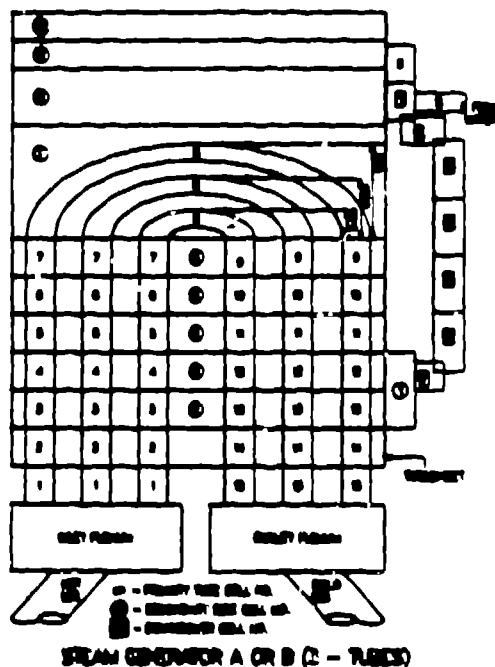
Circulation mode transitions were observed as the primary-side mass inventory was decreased. The three major modes observed were single-phase natural circulation, two-phase natural circulation, and reflux condensation. In all of these circulation modes, and during the transition between

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Initially, the three-tube SG did not account for heat transfer across the plenum divider plate and tube sheet, and as a result overpredicted the steady-state natural-circulation flow rate for 100% primary-side mass inventory by about 25% and overpredicted the SG inlet plenum temperature. With the addition of plenum heat transfer, the natural-circulation flow was within 3% of the observed flow. The hot-leg-to-plenum temperature drop and the fluid temperature distribution in the primary tubes of the SG3 were in excellent agreement with the data (see Fig. 6). The results for test ST-NC-01 (5% of scaled power) were equally as good (Ref. 3). The TRAC results indicate that reverse flow in the long tubes does not fully account for the temperature drop from the hot leg to the SG inlet plenum; part of this temperature drop is the result of heat transfer across the plenum divider plate and tubesheet.

B. Transient

In test ST-NC-02, the transient consisted of a series of drains of primary fluid through a letdown line at the bottom of the pressure vessel; each drain removed approximately 5% of the original primary mass inventory. After each drain the system was allowed to reach steady-state conditions. Although the valve in the pressurizer surge line was closed during the test, after the second drain there were changes in the pressurizer level indicating that there was flow between the pressurizer and the loop-A cold leg through the spray line.

Initially, the TRAC model simulated drainage of primary fluid through the letdown line in the vessel and flow into and out of the pressurizer by means of FILL components and tabular data for the flow rates, which matched the experimental data. In this mode of simulation, TRAC was calculating both the system pressure and the hydrodynamic response using the experimental data to establish the flow boundary conditions. Using this method, TRAC predicted a more rapid drop in system pressure and a more rapid increase in loop flow for each successive drain than was observed in the data. TRAC also predicted an increase of about 40% in SG heat transfer, steam flow, and feedwater flow during the first several drains. The excessive heat transfer to the secondary side overcooled the primary fluid and decreased the primary-side pressure below that of the data. Attempts to decrease the heat transfer by restricting the steam and feedwater flow and increasing the secondary-side pressure did not have a significant effect on the increases in the SG heat transfer. After several drains, the system pressure and loop flows calculated by TRAC differed greatly from that of the experiment, and no further calculations were made in this mode.

Since the valve in the pressurizer surge line was closed during the test, the observed changes in the pressurizer liquid level indicated that there was flow in the spray line connecting the loop-A cold leg to the pressurizer. To simulate this flow, a BREAK component was added to the cold-leg spray line along with a pressure table that matched the test data. In this mode of simulation, TRAC was calculating the hydrodynamic response of the system using the experimental data to establish the flow and pressure boundary conditions. It was found that the steam mass entering the system at the BREAK component in the cold leg was much greater than could be expected from the pressurizer. It was felt, however, that maintaining the correct system pressure was essential in order to predict

the hydrodynamic response of the system, and this simulation mode was used for the TRAC calculation. The disadvantage of this technique was that the steam mass, added to the system through the BREAK component to maintain the correct pressure, decreased the net mass removed from the primary system during each drain, particularly the first few drains. As a result, after 14 drains only 55% of the primary-system mass had been removed (see Table II).

TABLE II

PRIMARY MASS INVENTORY AS A FUNCTION OF NUMBER OF DRAINS (TRAC)

Drains	Primary Mass Loss (kg)[a]				Primary Mass Inventory (%)	
	Press.	Spray	Letdown	Net	TRAC	DATA
1	68.5[b]	52.5	-257.5	-136.4	97.3	95
2	64.0	152.3	-632.7	-387.4	94.4	90
3	-40.0	354.2	-799.6	-544.4	90.3	85
4	-54.2	422.5	-1064.3	-696.0	86.4	80
5	-38.6	568.1	-1337.8	-899.3	84.2	75
6	-31.6	786.3	-1611.6	-887.7	81.6	70
7	-35.2	753.6	-1865.4	-1157.0	77.3	66
8	-21.0	600.4	-2199.2	-1270.6	76.1	60
9	-15.2	1090.2	-2433.5	-1389.5	72.9	56
10	-10.4	1100.6	-2706.7	-1607.5	68.5	50
11	-6.8	1124.6	-2981.1	-1862.3	63.5	46
12	-1.7	1086.4	-3280.6	-2174.9	57.4	40
13	2.9	982.7	-3534.2	-2556.6	49.9	36
14	6.2	996.6	-3800.5	-2830.7	44.4	36
15	6.3	1090.1	-4064.5	-3060.1	40.6	
16	6.3	1115.1	-4319.4	-3198.0	37.3	
17	6.3	1212.5	-4574.3	-3365.5	34.2	
18	6.3	1330.4	-4829.3	-3502.6	31.3	
19	6.3	1435.0	-5084.2	-3642.9	28.6	
20	6.3	1550.1	-5330.1	-3774.7	26.0	

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[a] Integrated values.

[b] (−) Flow out of primary system.

(+) Flow into primary system.

Figure 7 is a plot of the loop mass flow as a function of primary mass inventory comparing TRAC predictions with the data. The TRAC results show a more rapid increase in mass flow as the primary mass inventory is reduced and reaches a peak value of 15.47 kg/s, which is about 50% greater than the maximum loop flow observed in the test. The peak flow in the TRAC calculation and the data occurred at the same primary mass inventory. The natural-circulation flow in the experiment stopped at a primary mass inventory of about 63%; TRAC predicted the loop flow to stop at a mass inventory of approximately 55%. If there were any air trapped in the system it may have accounted, in part, for the smaller loop flow and earlier terminating of natural-circulation flow. With only six instrumented tubes, it is not possible to determine if some of the noninstrumented tubes were stagnant in the test. Another possible explanation for TRAC's overpredicting

the natural-circulation flow is the steam flow into the primary system through the BREAK component in the cold-leg spray line. The steam addition required to maintain the proper system pressure results in a temperature excursion in the cold leg, which propagates throughout the primary system. In Fig. 8 it can be seen that during the drain periods. TRAC predicts that the liquid temperature in the upflow leg of SG A increases. This effect was not seen in the data. The increased temperature in the upflow leg leads to a greater pressure difference between the SG plena and a greater temperature difference between the primary and secondary fluid. The result is greater flow in the SG tubes and increased SG heat transfer. This tends to decrease the primary-system pressure, which requires additional steam flow into the primary at the cold-leg spray line. The TRAC inventory values represent the active or primary-system mass.

The TRAC calculation indicates that the natural-circulation flow mode in the SG tubes changed from single-phase to two-phase to reflux condensation. The cyclic fill and dump mode seen briefly in the test as the tubes drained was not predicted by TRAC. The flow in the SG U-tubes stopped and the reflux condensation mode started when the tops of the tubes completely voided. TRAC predicted that the flow in the short tube stopped at a primary mass inventory of about 81%, at which time reverse flow in the long tube changed to flow in the forward direction. The flow stopped in the medium tube at a primary mass inventory of approximately 69%. Loop flow completely stopped at a primary mass inventory of about 55%. After this time liquid flowed down both legs of the U-tube, indicating that reflux condensation had begun. Vapor velocities indicated that the void region received steam from both the upleg and the downleg of the SG, replacing the condensed vapor.

Both the data and TRAC results indicate that at a primary mass inventory of 90%, voids were detected in the hot legs and in the lower part of the upflow legs of the SGs. Complete condensation occurred in the lower part of the SG tubes. In the test, voids reached the top of the U-tubes at a mass inventory of 84%. TRAC predicted that the U-bend of the short tube was completely voided at this primary-side mass inventory and flow in the short tube had stopped. Both TRAC and the data indicate that reversed flow in the long tubes stopped, and normal flow started at a mass inventory of approximately 80%. The data indicate that at a mass inventory of 75% the U-tube differential pressure became negative and all tubes showed forward flow. At this mass inventory, TRAC predicted that the short- and medium-length tube were voided at the top of the U-bend and only the long tube had normal flow. In the test the middle-length tubes are the first to void and enter the reflux condensation mode at a mass inventory of about 70%. TRAC predicted that the medium tube voided after the short tube and began the reflux condensation mode at a mass inventory of about 75%. Reflux condensation cooling continued until the mass inventory was reduced to approximately 35%; the primary side of the SG tubes was filled with saturated steam at this time. The temperature of the SG tubes was uniform and approximately equal to that of the secondary-side fluid.

As the primary mass inventory was decreased further, the hot legs and primary side of the SGs completely voided; most
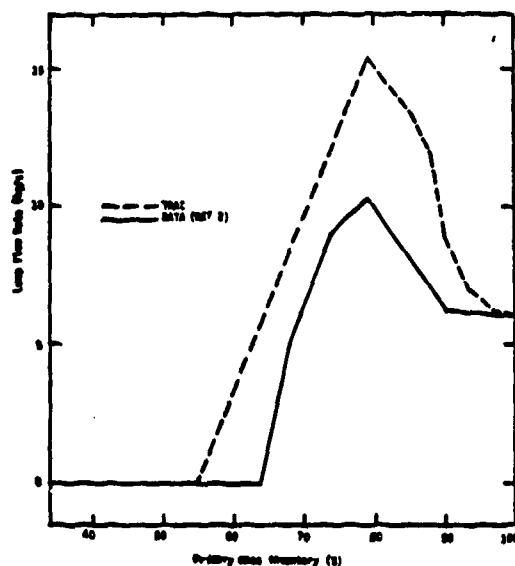

Fig. 7.
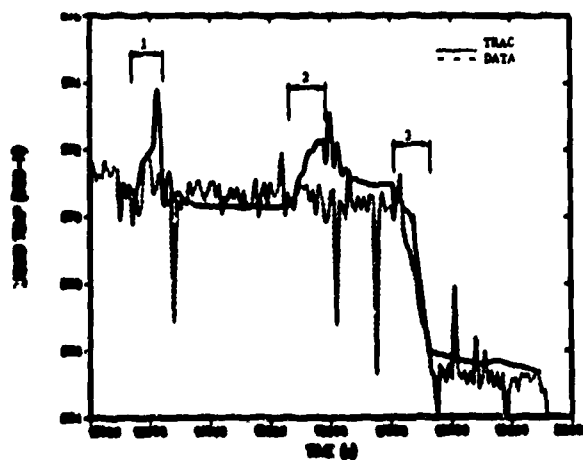Primary-loop flow rate as a function of primary mass inventory test ST-NC-02.

Fig. 8.
Primary temperature SG A short-tube elevation 8.61 m.

of the remaining mass inventory was contained in the loop seals and vessel. At a mass inventory of approximately 30%, TRAC predicted adequate core cooling. During the next drain, the upper levels of the core began to uncover and heat up; the mass inventory being about 27% at this time. This is

in moderate agreement with the experimental results cited in Ref. 4.

CONCLUSIONS

A TRAC model of the LSTF, including a 3-tube SG model, was used to analyze natural-circulation test ST-NC-02. TRAC was able to predict the major phenomena that occurred in the steady state for a primary mass inventory of 100%. Reverse flow in the long SG tubes was predicted. The calculated temperature distribution in the SG tubes and the temperature drop from the hot leg to the SG inlet plenum was in excellent agreement with the data. The natural-circulation flow rate in the loops was predicted within 3% of that observed in the data. Heat transfer across the plenum divider plate and the tube sheet was found to be significant in matching the loop flow rate and hot-leg-to-SG-plenum temperature drop in the test. TRAC predictions indicate that reverse flow in the SG tubes does not fully account for the SG inlet-plenum temperature drop.

As the primary-system mass was reduced, TRAC overpredicted the pressure decrease and the loop flow rate. The addition of a BREAK component at the cold-leg spray line permitted the system pressure to be duplicated, but the steam flow into the cold leg was greater than could be expected because of flow from the pressurizer. This resulted in temperature excursions, which propagated throughout the primary system increasing the flow rate and heat transfer in the SGs. TRAC predicted voiding and flow stoppage in the tubes at higher primary-mass inventories than seen in the test and did not predict the cyclic fill and dump phenomenon. TRAC was able to predict the single-phase and two-phase natural-circulation modes and the reflux-condensation phenomenon. TRAC predicted a peak-loop mass flow at the same mass inventory as the test data but the maximum mass flow rate was overpredicted by approximately 50%. The core is well cooled at this time, so the overprediction of mass flow is not nonconservative.

The greater loop flow predicted by TRAC is partially the result of the SG modeling and the greater SG heat transfer calculated by TRAC. There are nine tube lengths in the facility SGs, and the flow in any tube may be different than that in any other tube. The choice of 3 tubes to model the 141 U-tubes in the ROSA-IV SGs requires that the tube flow patterns be characterized by 1 of 3 behaviors, and each such behavior is assumed to occur in more than 40 tubes. The SG heat transfer calculated by TRAC may be collapsing the voids too rapidly, thus decreasing the system pressure and increasing the calculated system flow. The experimental flow may have been low because of air in the system, and the flow predicted by TRAC was high because of the SG heat transfer.

The apparent flow reversal in the longest tubes of the 141-tube SG in the LSTF during the natural-circulation tests also occurred in the 6-tube SG in the Semiscale facility. It is expected that this phenomenon will also occur in a full-scale plant and will lead to less natural-circulation flow than would be predicted without reverse flow in the long tubes. TRAC can be used to predict the reverse-flow phenomenon if a sufficiently detailed model is used for the SG primary side. The single-tube primary-side model is adequate for transients where the detailed flow pattern in the SG is not important.

but the additional losses caused by the flow pattern should be added to predict the natural-circulation flow.

One of the most important results of this analysis is that TRAC predicted the primary mass inventory at which inadequate core cooling occurs. When the primary mass inventory is reduced below about 30%, the highest-power rods begin to heat up.

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